



ESSnuSB OPEN MEETING 13-14 March 2014

# LAGUNA/LBNO PHYSICS CASE

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On behalf of the LAGUNA/LBNO collaboration

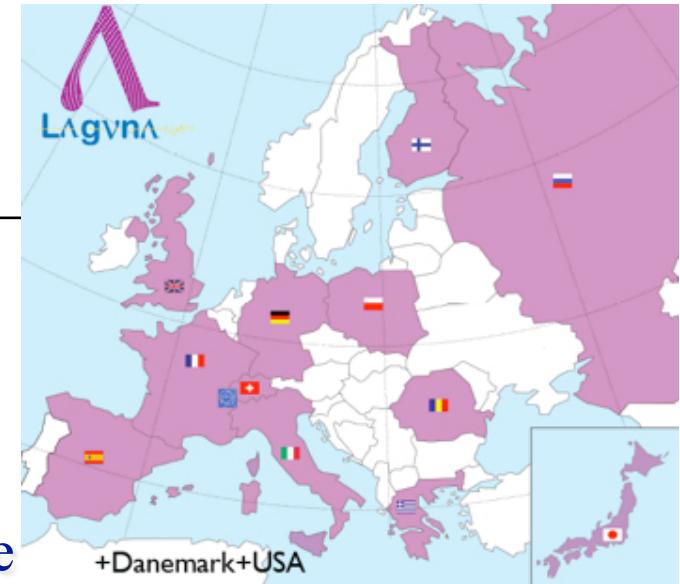
# OVERVIEW

- **THE LAGUNA LBNO PROJECT**
- **LBNO AT GARPENBERG**
  - MASS HIERARCHY SENSITIVITY (SPS & HPPS beam)
  - DELTA CP SENSITIVITY (SPS & HPPS beam)
- **CONCLUSIONS**

# LAGUNA/LBNO consortium

Large Apparatus for Grand Unification and Neutrino Astrophysics  
and  
Long Baseline Neutrino Oscillations

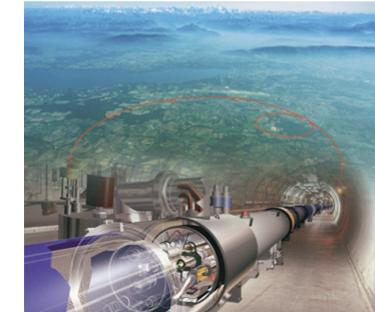
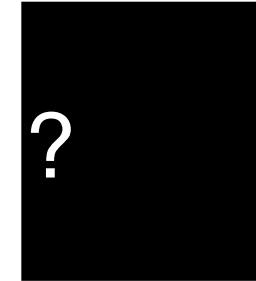
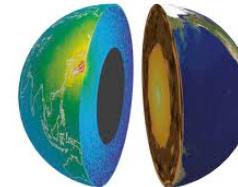
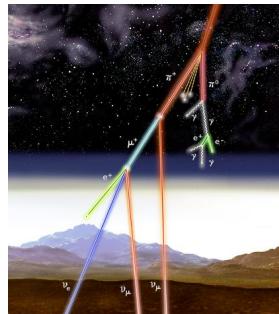
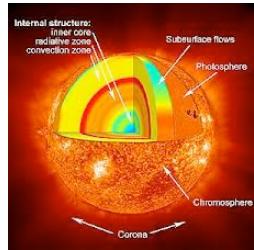
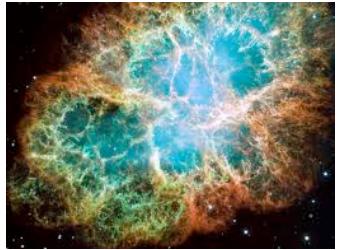
- **LAGUNA DS (FP7 Design Study 2008-2011)**
  - ~100 members; 10 countries, 1.7 M€
  - 3 detector technologies  $\otimes$  7 sites,  
different baselines (130 → 2300km)
- **LAGUNA-LBNO DS (FP7 DS Long Baseline  
Neutrino Oscillations, 2011-2014)**
  - ~300 members; 14 countries + CERN, 4.9 M€
  - Down selection of sites & detectors
- **LBNO (CERN SPSC EoI for a very long baseline  
neutrino oscillation experiment, June 2012)**
  - An incremental approach, based on the findings of LAGUNA
  - ~230 authors; 51 institutions
  - CERN-SPSC-2012-021 ; SPSC-EOI-007 -> **WA105 Large scale prototype at CERN**



**Steering group:**  
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Yuri Kudenko (INR)  
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Marco Zito (CEA)



# LBNO: Large Apparatus for Grand Unification and Neutrino Astrophysics and seline Neutrino Oscillations



## LAGUNA Physics:

### 1. Accelerator based:

- Mass Hierarchy
- $\delta_{CP}$
- MSNP precision
- 3 v or 3+n ?

large  $\theta_{13}$

### 2. Non-Accelerator based:

- Proton decay

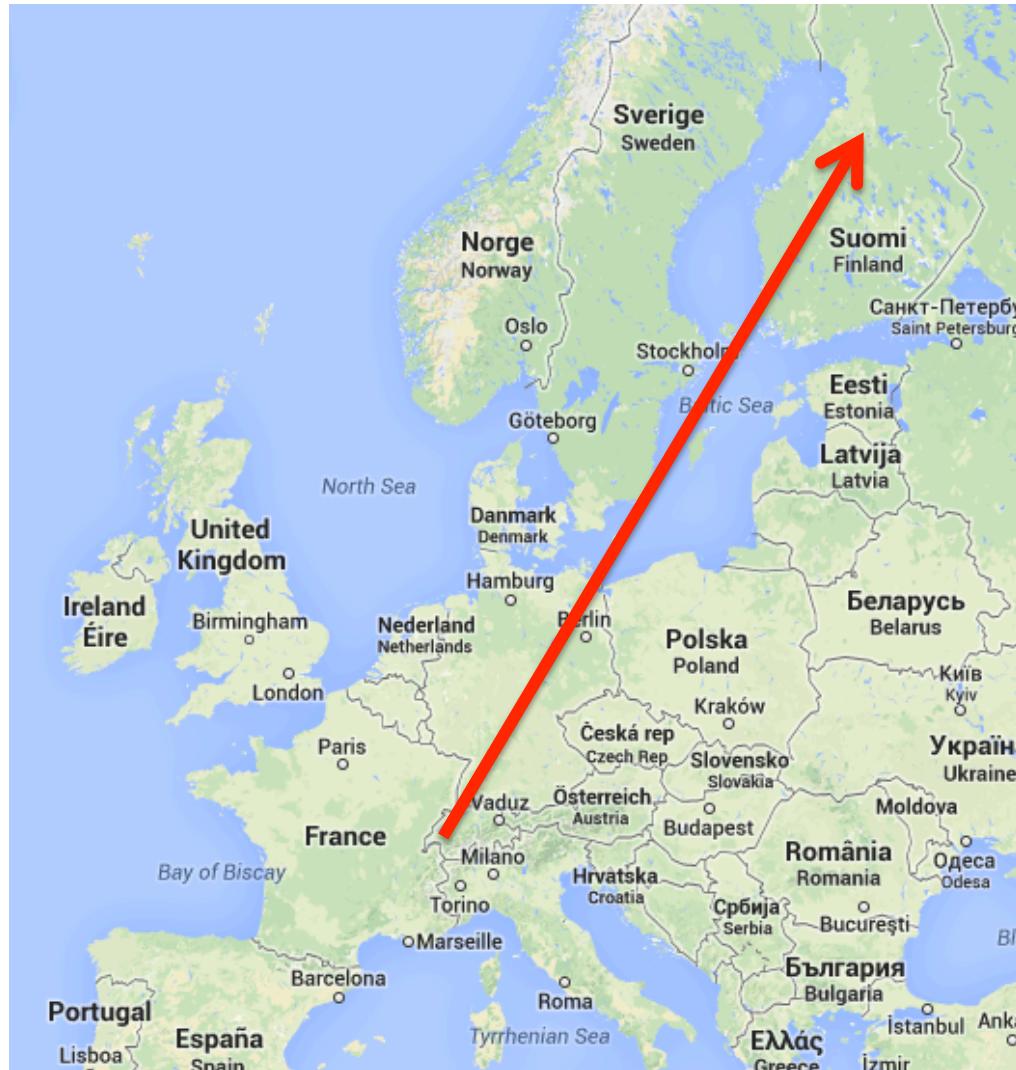
### 3. Neutrino Astronomy:

- Supernova neutrinos
- Diffuse Supernova Neutrinos (DSN)
- Solar Neutrinos
- Atmospheric Neutrinos

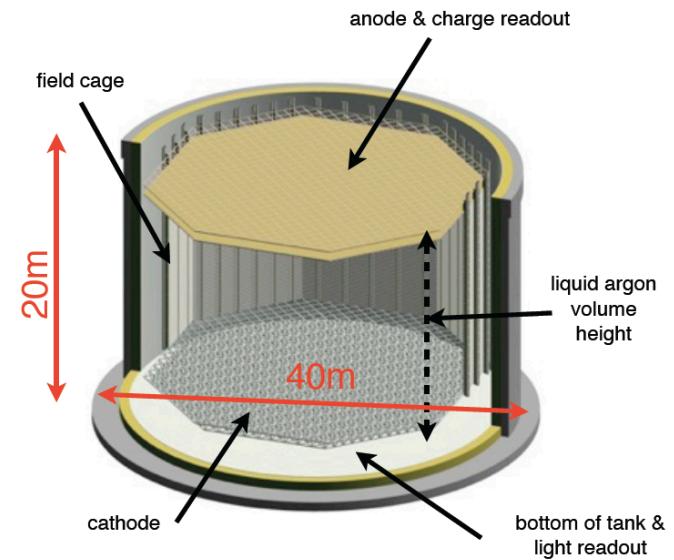
### 4. Dark Matter

The highly important discovery of the Higgs at CERN July 4<sup>th</sup> 2012 has crowned the SM, Neutrino physics provides us with surprises!

# LAGUNA/LBNO CERN TO PHYÄSALMI CN2PY:



- 2300 km baseline from CERN (CN2PY)
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid Argon double phase detector  
GLACIER : 20 kt up to 70 kt



# Strategy

- Based on the findings from LAGUNA and LAGUNA-LBNO the collaboration decided to put forward a concrete proposal for the future neutrino observatory in 2012, EoI 007 to CERN.
- We have compared 7 locations in Europe and conducted precise estimations on the costs of the facility, of the detector and of the beam.
- We compared the physics potential of all possible combinations - detector - location - beam.
- **The conclusion is to propose a neutrino observatory with a clear long-term strategy in a deep underground location at the longest baseline proposed, 2300 km, compatible with:**
  - A full astro-particle program
  - Competitive nucleon decay measurements wrt SK and
  - An incremental long-baseline program with a competitive 1st stage guaranteeing high level physics performance from the beginning. (e.g. MH at  $5\sigma$  CL with ~100% power in ~5years)
  - Stage 1 is based on a 20 kt fid. LAr detector (double phase) and a conventional beam from the CERN SPS of 700 kW.
  - Measure of the 1st and 2nd oscillation maxima and the L/E behavior
- If the findings from stage 1 require, the detector and the beam will be upgraded to 70 kt and 2 MW.
- The location of the infrastructure is perfectly adapted to a neutrino factory, allowing the ultimate measurements in the accelerator neutrino field.

# LAGUNA/LBNO ASSUMPTION: OSCILLATION PARAMETERS AND NORMALISATION

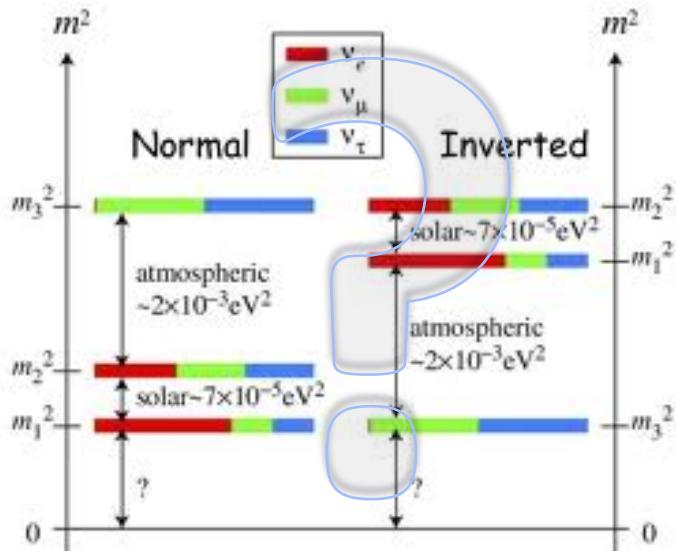
## CONSERVATIVE VALUES FOR OSCILLATION PARAMETERS PRIORS AND SYSTEMATICS

10.1007/JHEP12(2012)123

Name	Value	error ( $1\sigma$ )	error (%)
L	2300 km	exact	exact
$\Delta m_{21}^2$	$7.6 \times 10^{-5} \text{ eV}^2$	exact	exact
$ \Delta m_{31}^2  \times 10^{-3} \text{ eV}^2$	2.420	$\pm 0.091$	$\pm 3.75 \%$
$\sin^2 \theta_{12}$	0.31	exact	exact
$\sin^2 2\theta_{13}$	0.10	$\pm 0.01$	$\pm 10\%$
$\sin^2 \theta_{23}$	0.440	$\pm 0.044$	$\pm 10\%$
Average density of traversed matter ( $\rho$ )	3.20 g/cm <sup>3</sup>	$\pm 0.13$	$\pm 4\%$

Name	Value	error ( $1\sigma$ )
Signal normalization ( $f_{sig}$ )	1	$\pm 5\%$
Beam electron contamination normalization ( $f_{\nu_e}$ )	1	$\pm 5\%$
Tau normalization ( $f_{\nu_\tau}$ )	1	$\pm 20\% - \pm 50\%$
$\nu$ NC and $\nu_\mu$ CC background ( $f_{NC}$ )	1	$\pm 10\%$

# LBNO STRATEGY ON MASS HIERARCHY



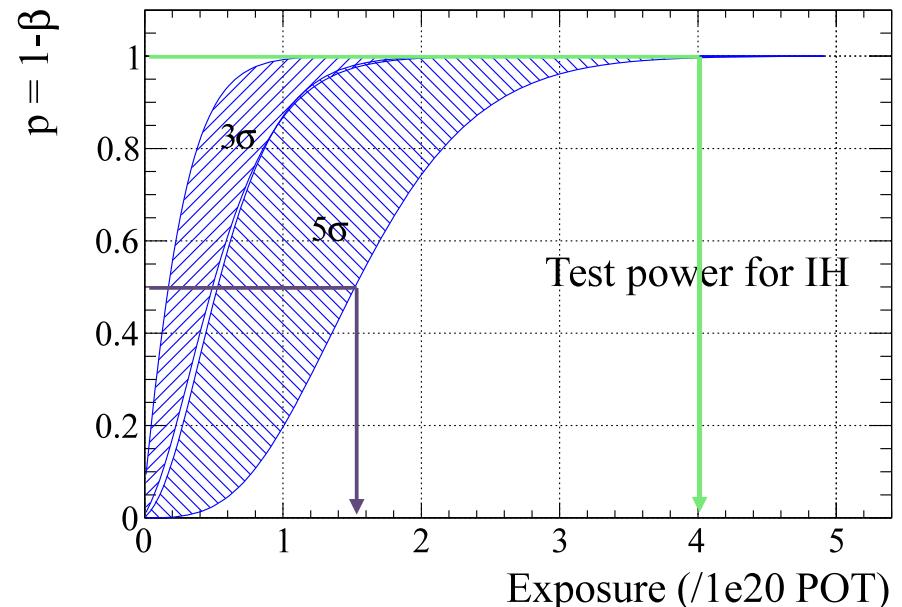
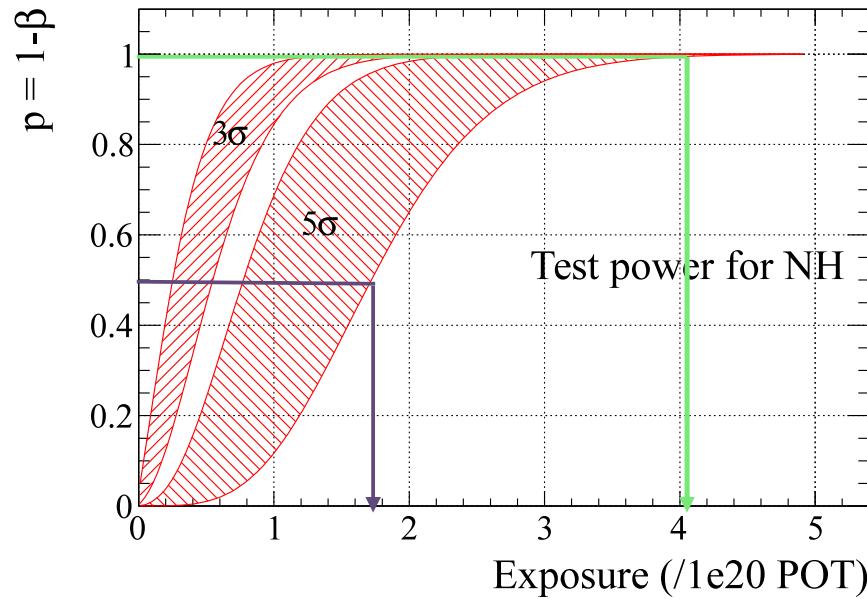
- MH is a **prerequisite** to study leptonic CPV
- Scenarios for lepto-genesis
- Hints for theory development (GUT models)
- Feasibility and interpretation of Onbb experiments
- Interpretation of HDM from cosmology in terms of  $\nu$  masses

## LBNO strategy on MH:

- To guarantee the measure MH on the  $> 5\sigma$  level one need to go to very long baselines  $> 2000$  km,  $\sim 1000$  km gives not enough MSW to measure the full phase space.
- The **median  $5\sigma$  sensitivity** ( $p = 0.5$ ) for LBNO is reached within 2 years of running.
- The **guaranteed  $5\sigma$  sensitivity** ( $p = 1$ ) for LBNO is reached within 5 years of running.
- Global fits of many experiments can guide and help the research but cannot replace the measurement of a dedicated experiment.
- LBNO aims at exploring and resolve the mass hierarchy and the CP-phase problem by observing clear signatures and ascertaining their L/E dependence.

# LBNO STRATEGY ON MASS HIERARCHY

- Power vs exposure for all values of  $\delta_{CP}$  (shaded bands)



$p = 0.5 \Rightarrow$  “Median experiment”  
50% chance to give the wrong  
answer if the alternative hypothesis  
is true  
WOULD YOU BET 500 M€ ON SUCH  
AN EXPERIMENT ?

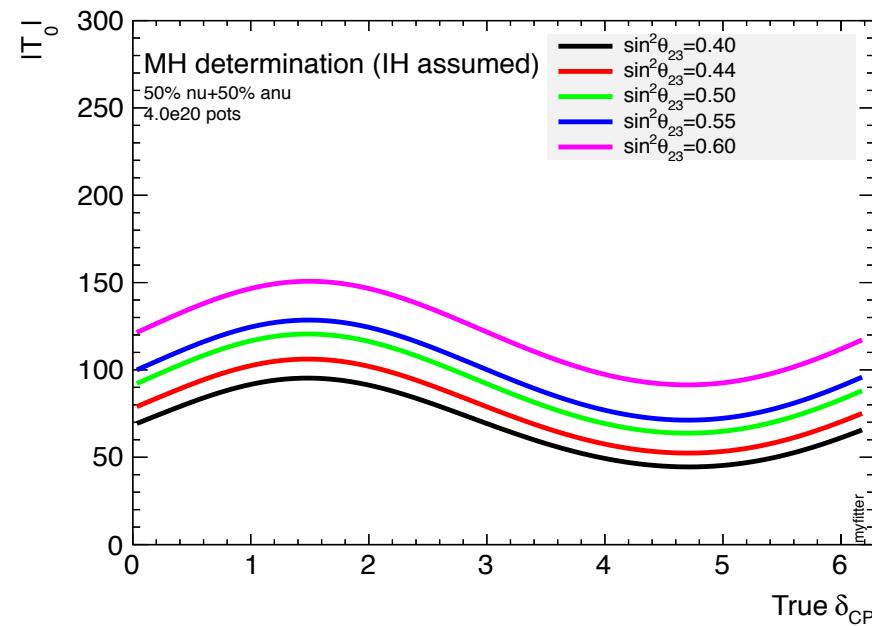
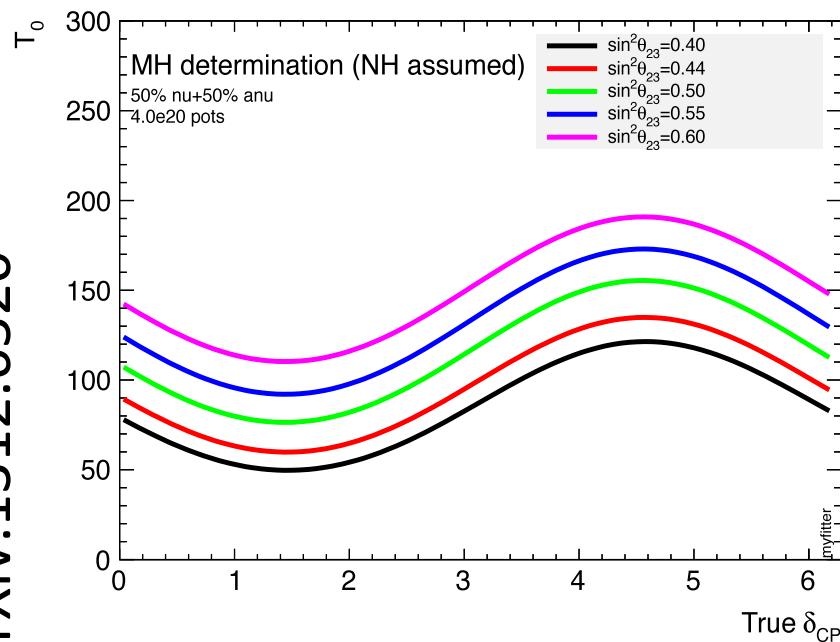
$p \sim 1 \Rightarrow$  “Full power experiment”  $\sim 0$   
chance to give the wrong answer if  
the alternative hypothesis is true

THE LBNO CHOICE TO QUOTE  
SENSITIVITY

# LBNO STRATEGY ON MASS HIERARCHY

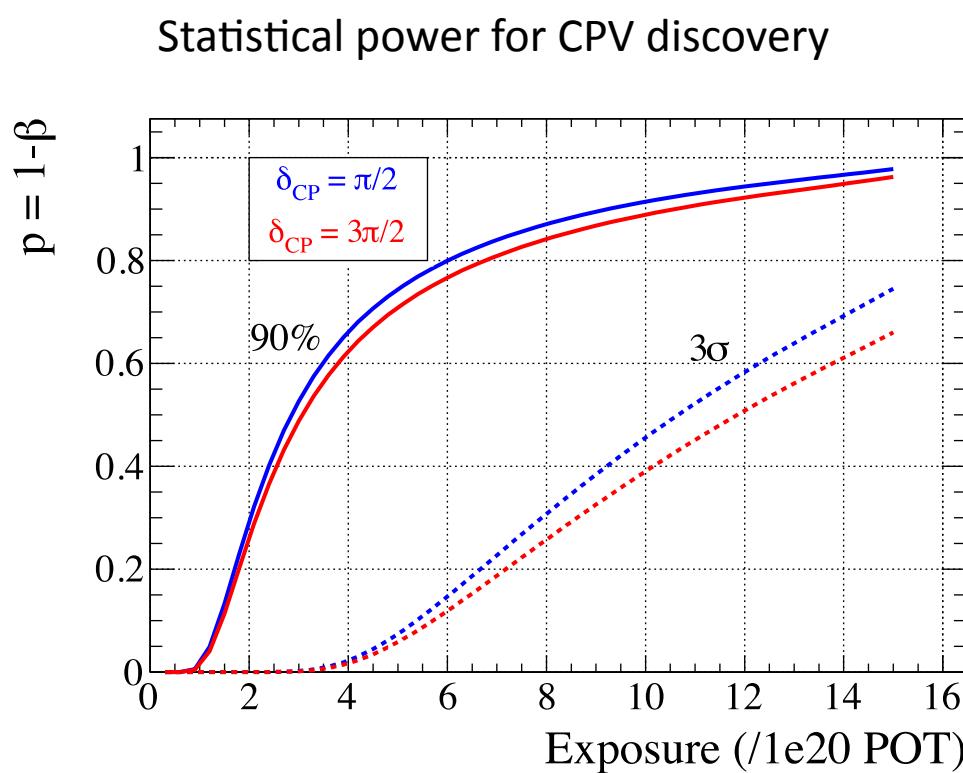
Mean value of the mass hierarchy test statistic as a function of true  $\delta_{CP}$  and the value of  $\sin^2\vartheta_{23}$  for an exposure of  $4 \times 10^{20}$  pots (or about 4 years of running at the SPS) and LBNO 20 kton LAr double phase detector.

arXiv:1312.6520

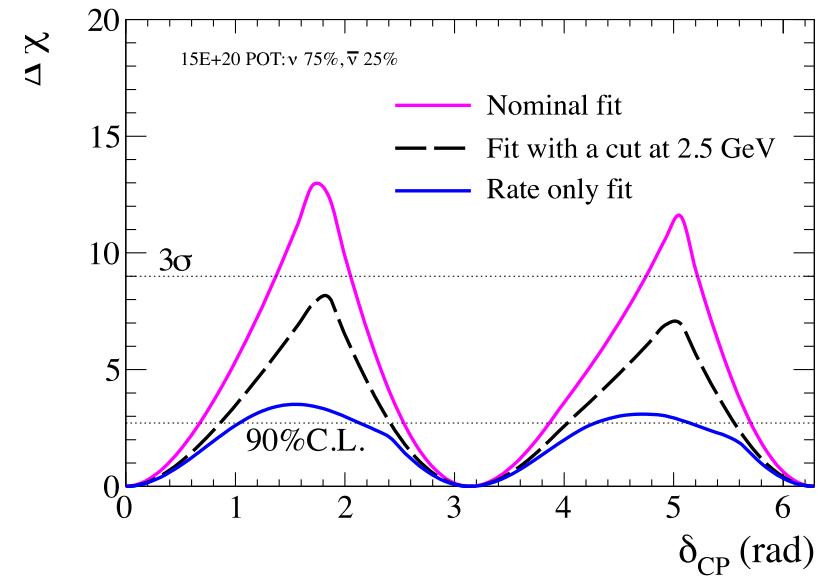


# LBNO STRATEGY ON $\delta_{\text{CP}}$

Once MH determined run for 5 more years to cover the most possible phase space in  $\delta_{\text{CP}}$ .



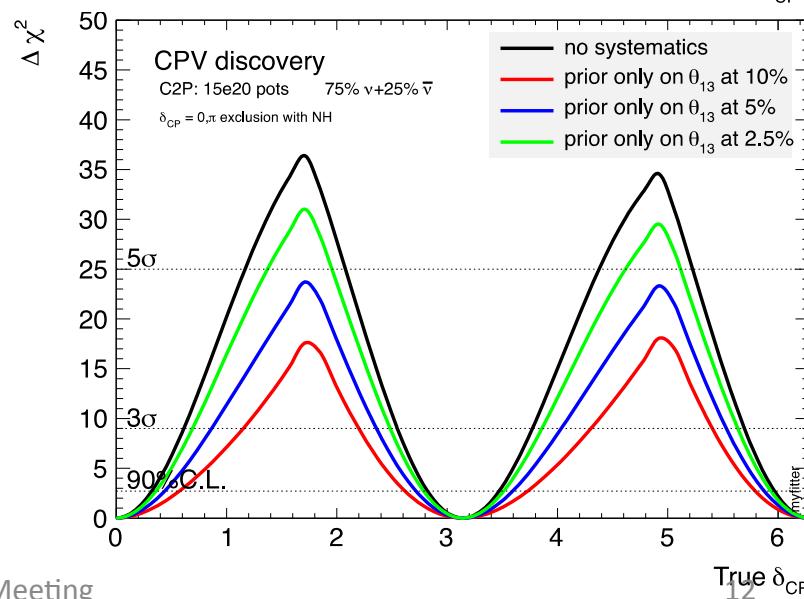
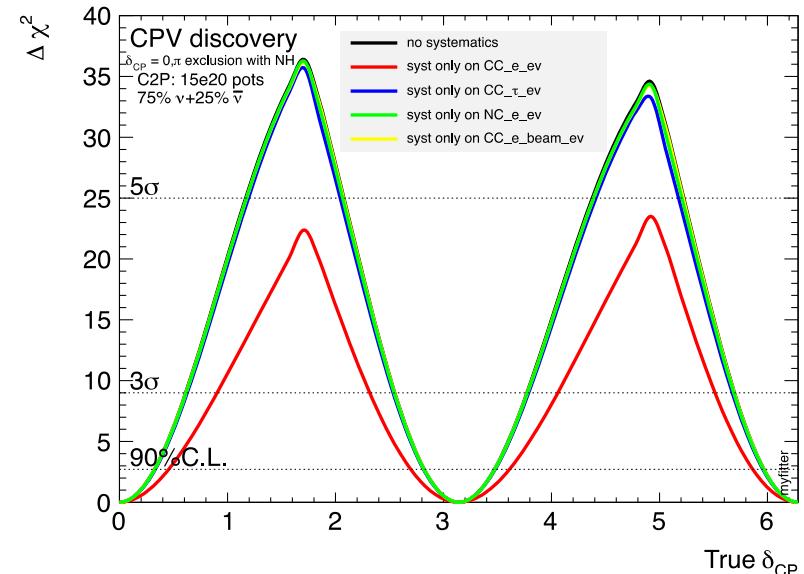
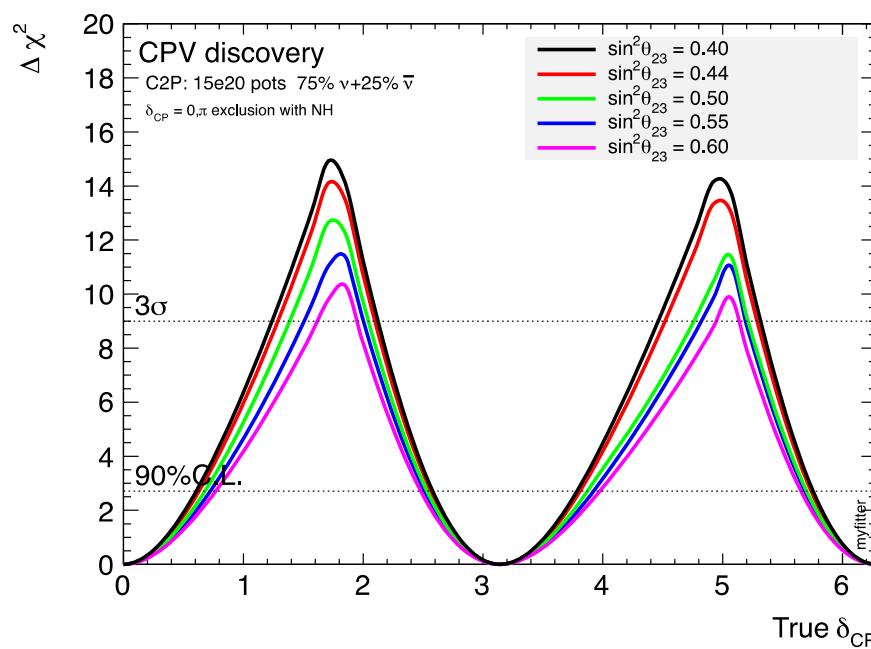
Use all spectral information: **Rate & Shape** for energy range 1<sup>st</sup> - 2<sup>nd</sup> max



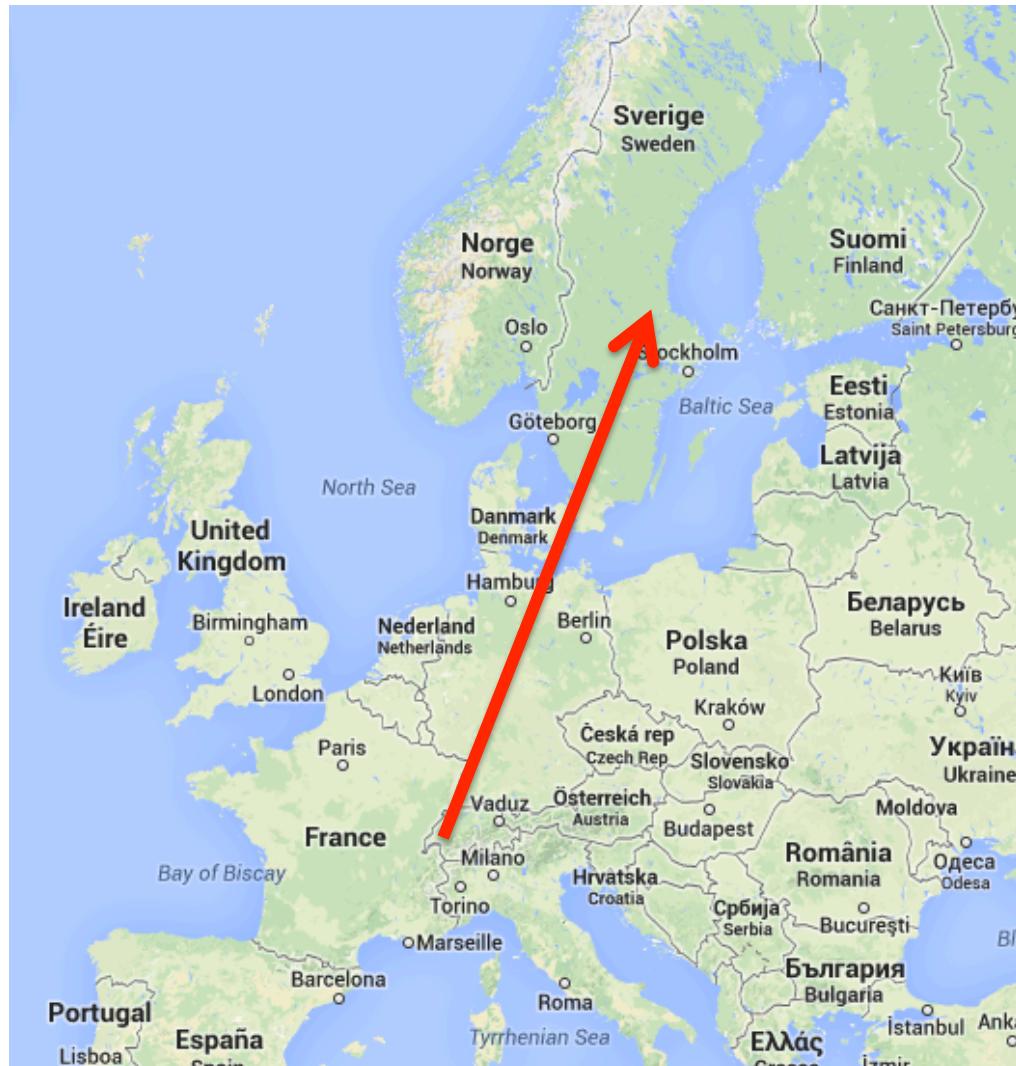
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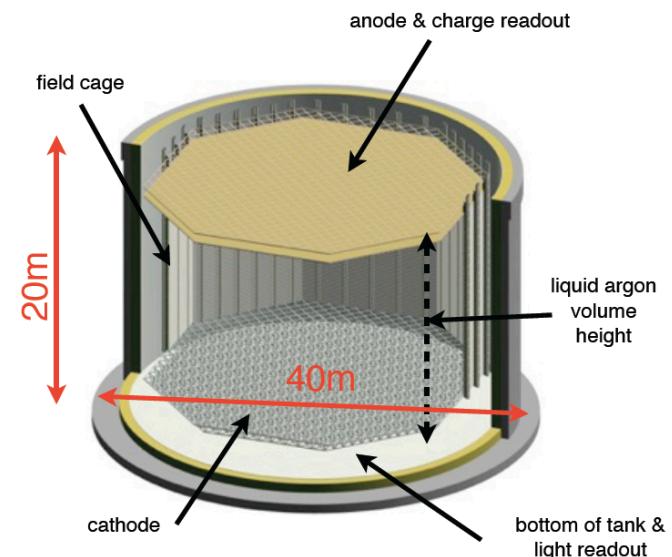
The most important oscillation parameters are  $\theta_{23}$  and  $\theta_{13}$  and the most important systematics is the knowledge of the absolute rate of  $\nu_e$  CC events.



# LBNO @ GARPENBERG: SENSITIVITY STUDIES FOR THE ESS PROJECT



- 1700 km baseline from CERN (CN2GA)
- SPS 400 GeV protons – 750 kW beam
- HPPS 50 GeV protons – 2 MW beam
- Liquid Argon double phase detector  
GLACIER : 20 kt up to 70 kt



# BEAM ASSUMPTIONS

Physics potential investigated with two beams:

- SPS beam (optimised for 2300 km)
- HPPS beam (renormalised SPS beam)

The simulation of LBNO@Garpenberg physics potential have been done with the CERN to PYHASALMI beam

## OSCILLATION MAXIMA AT 1700 km

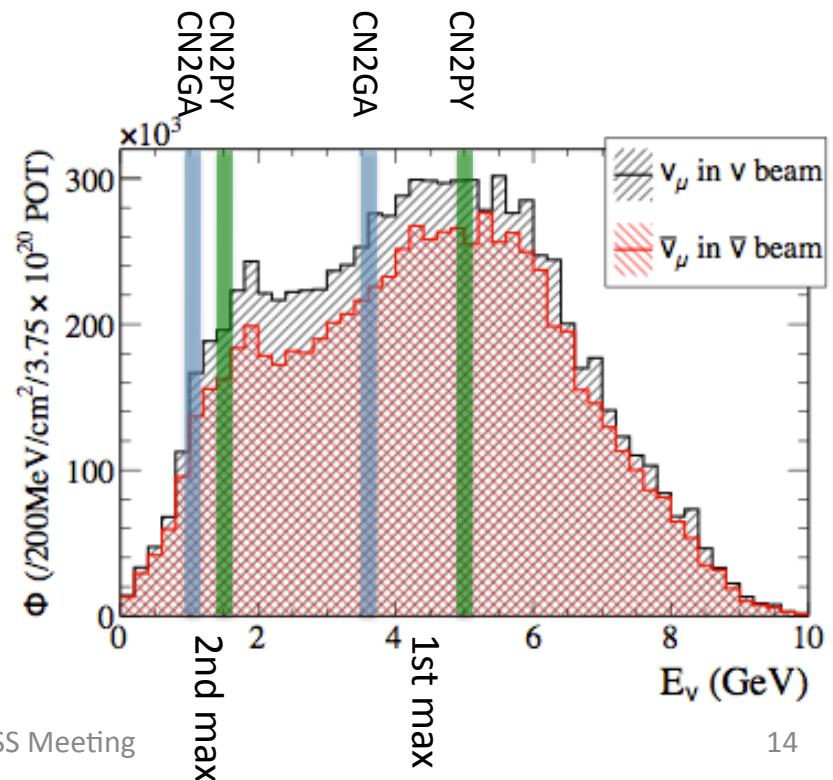
$$E \text{ (1st max)} = 3.30 \text{ GeV}$$

$$E \text{ (2nd max)} = 1.1 \text{ GeV}$$

- 1700 km oscillation maxima
- 2300 km oscillation maxima

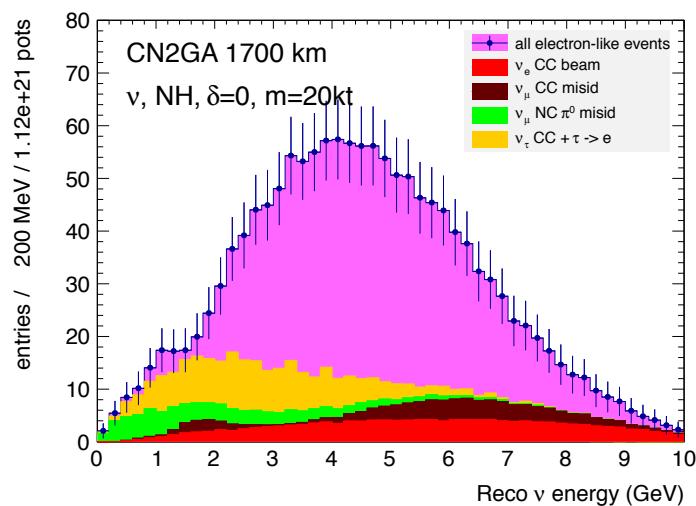
Parameter	SPS beam	HP-PS beam
$E_{\text{beam}} [\text{GeV}]$	400	$50 \div 75$
$I_{\text{beam}} [\text{ppp}]$	$7 \times 10^{13}$	$2.5 \div 1.7 \times 10^{14}$
Cycle length [s]	6	1
$P_{\text{beam}} [\text{MW}]$	0.750	2
$\text{POT}_{\text{year}} [10^{21}]$	$0.10 \div 0.14$	$3.46 \div 2.35$

CERN SPS BEAM OPTIMISED FOR 2300 km



# EXPECTED NUMBER OF EVENTS

Beam	$\nu_\mu$ unosc. CC	$\nu_\mu$ osc. CC	$\nu_e$ beam CC	$\nu_\mu$ NC	$\nu_\mu \rightarrow \nu_\tau$ CC	$\nu_\mu \rightarrow \nu_e$ $\delta_{CP} = -\pi/2, 0, \pi/2$
LBNO@Garpenberg: 1700 km 400 GeV, 750 kW $1.5 \times 10^{20}$ POT/year, NH 50kt years $\nu$ 50kt years $\bar{\nu}$	6309 2435	2438 948	40 10	2219 905	288 129	309 268 206 36 52 55
LBNO@Garpenberg: 1700 km 50 GeV, 2 MW $3.0 \times 10^{21}$ POT/year, NH 50kt years $\nu$ 50kt years $\bar{\nu}$	15756 6080	6087 2367	99 23	5542 2262	726 322	772 670 515 90 129 137

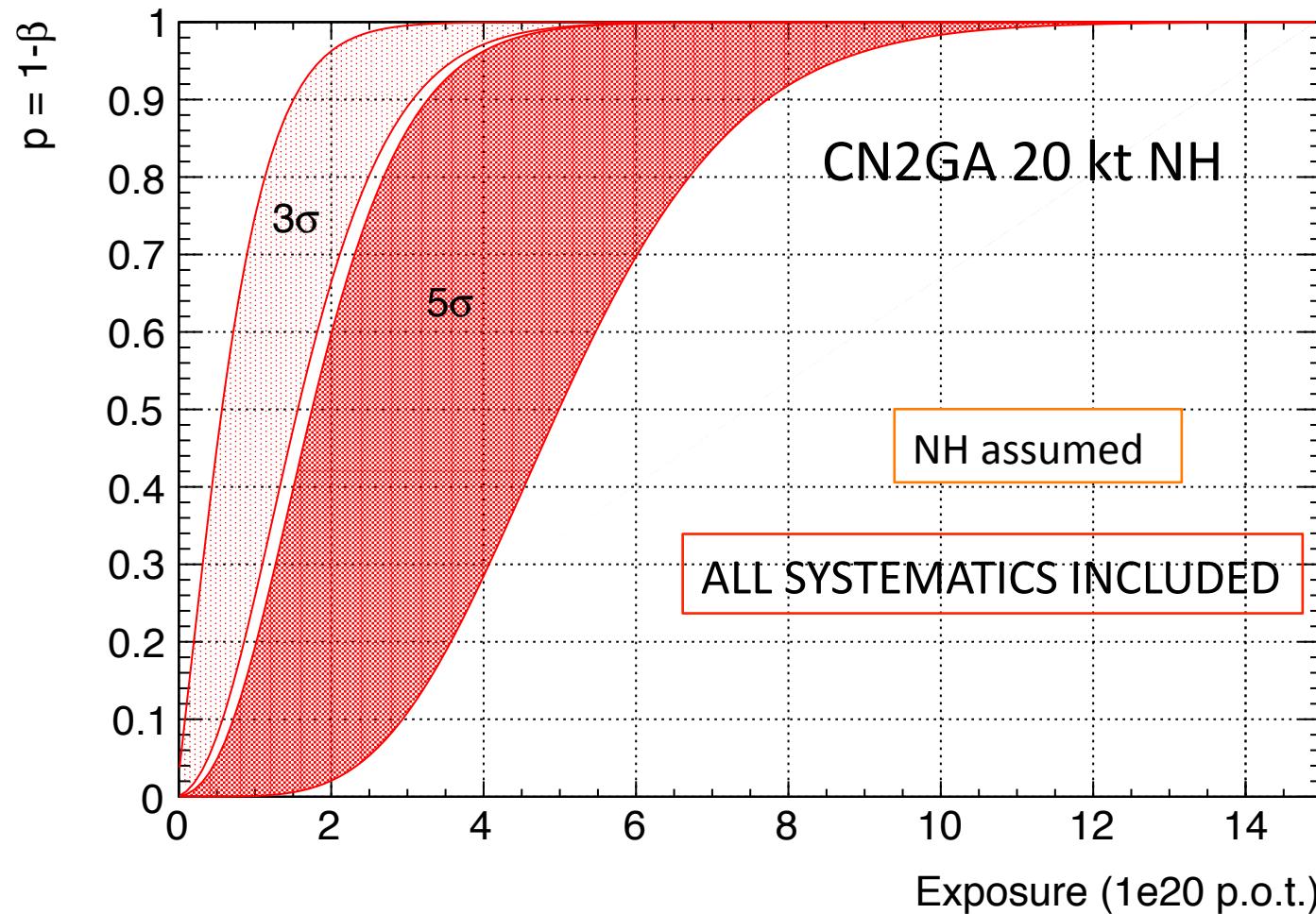


Oscillation event rates normalised to 50 kt year for the SPS and HPPS CN2GR beams (NH assumed)  
**NO detector efficiencies are taken into account**

# MASS HIERARCHY SENSITIVITY

## LBNO@GARPENBERG

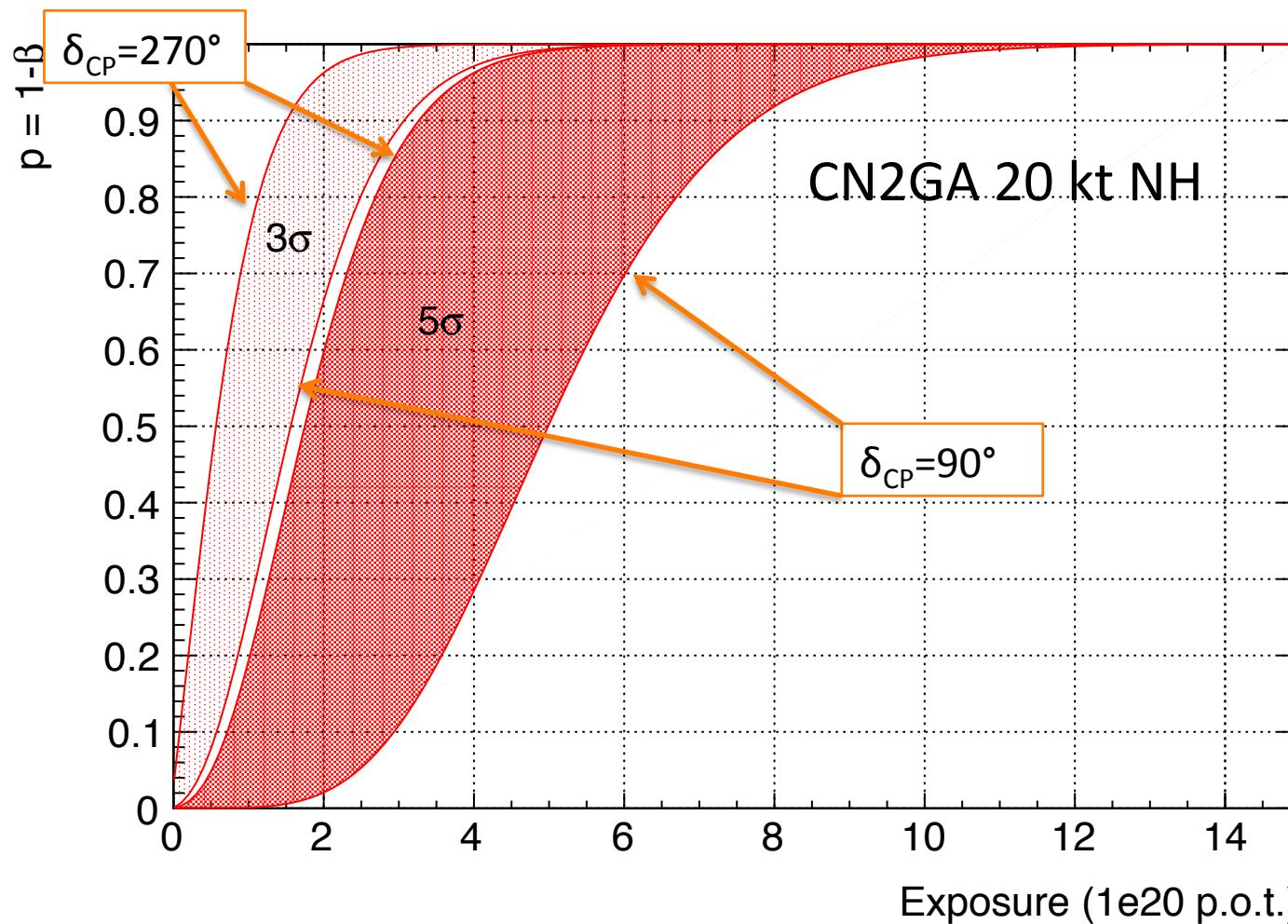
Power (NH) VS Exposure assuming 3 or 5 sigma Confidence Level  
20 kt SPS 400 GeV beam 1700 km



# MASS HIERARCHY SENSITIVITY

## LBNO@GARPENBERG

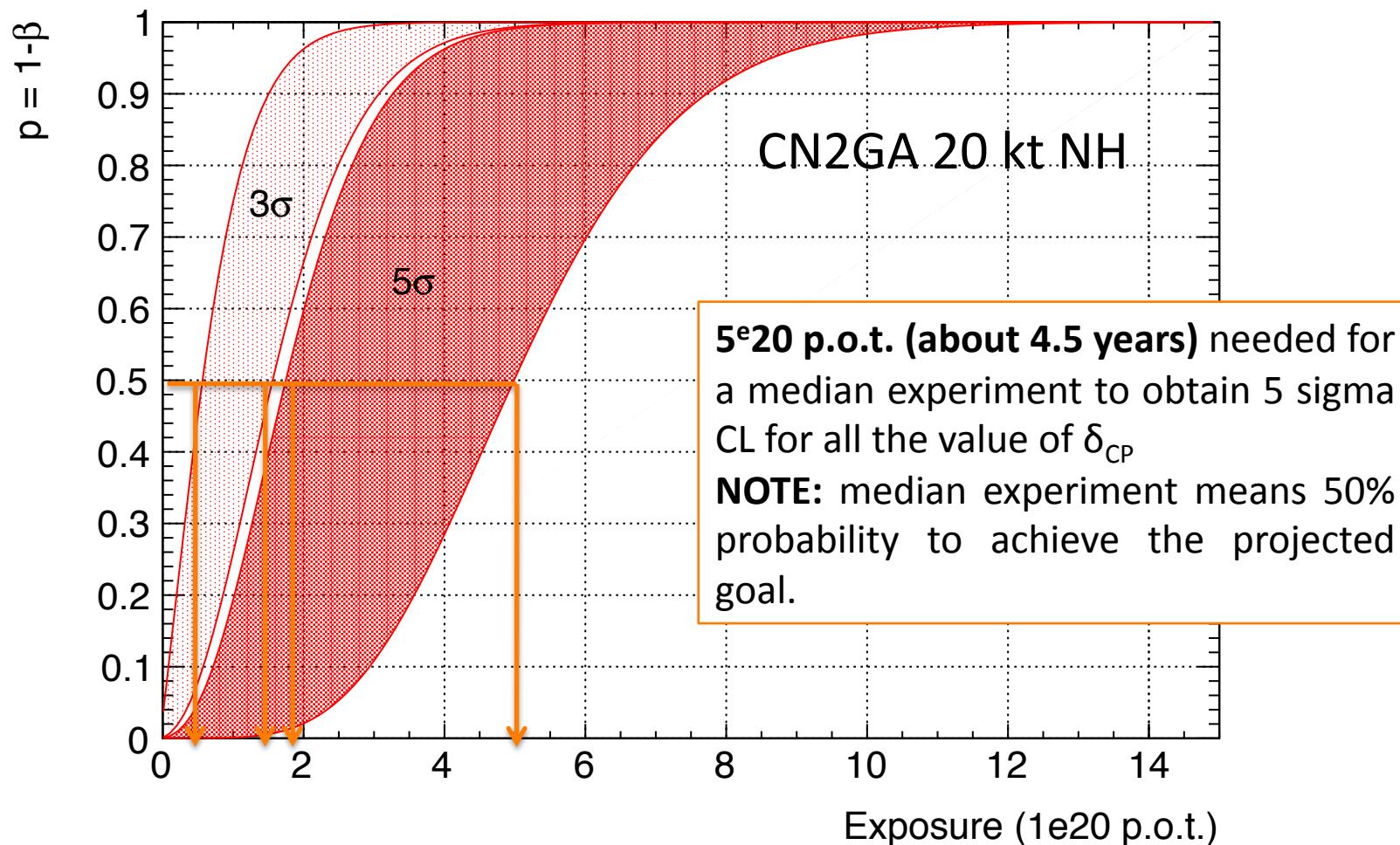
Power (NH) VS Exposure assuming 3 or 5 sigma Confidence Level  
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# MASS HIERARCHY SENSITIVITY

## LBNO@GARPENBERG

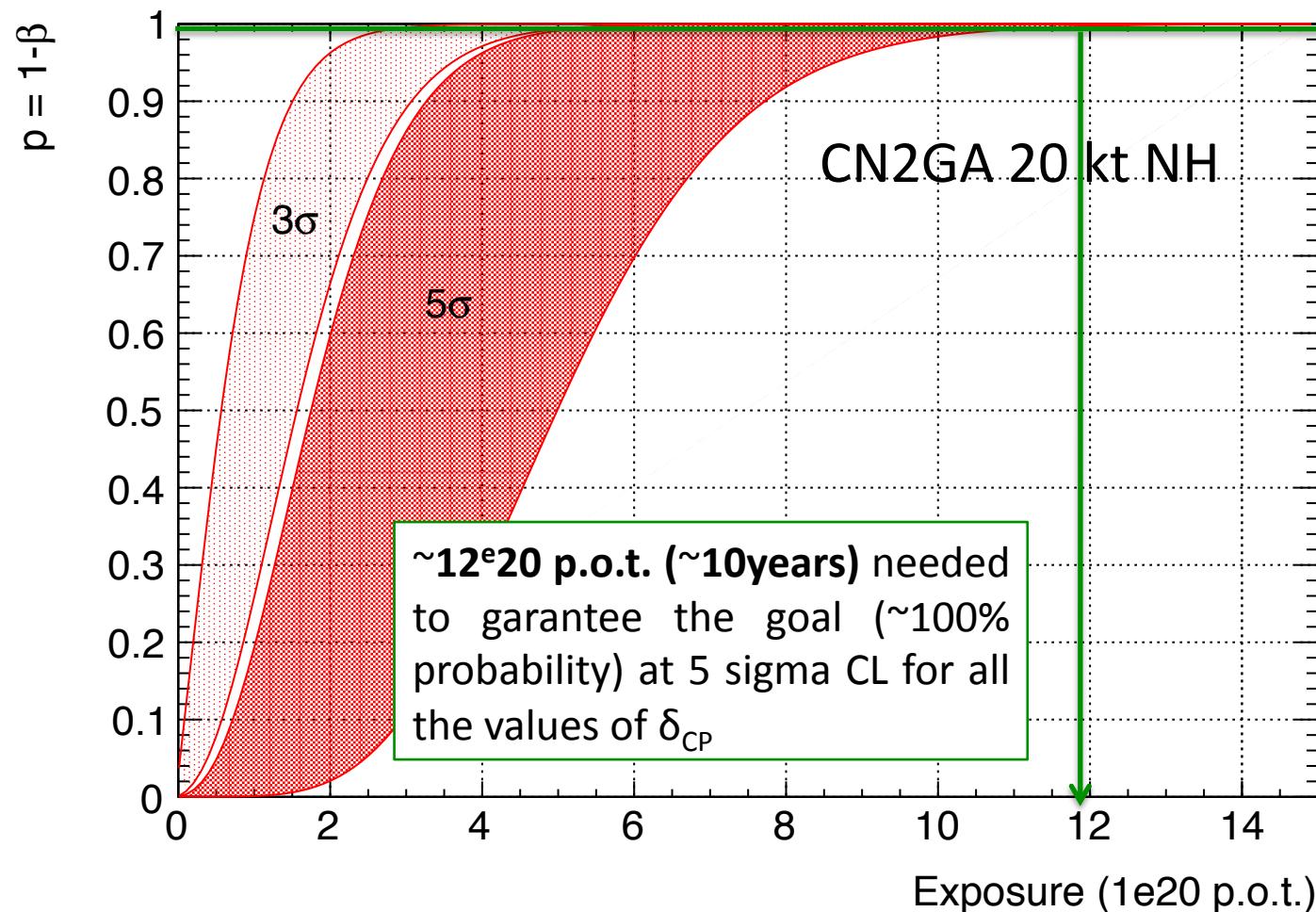
Power (NH) VS Exposure assuming 3 or 5 sigma Confidence Level  
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# MASS HIERARCHY SENSITIVITY

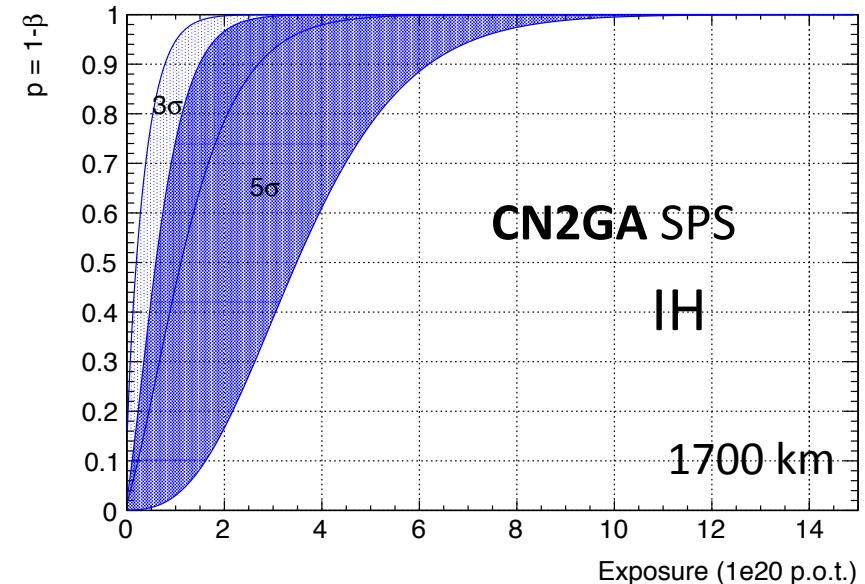
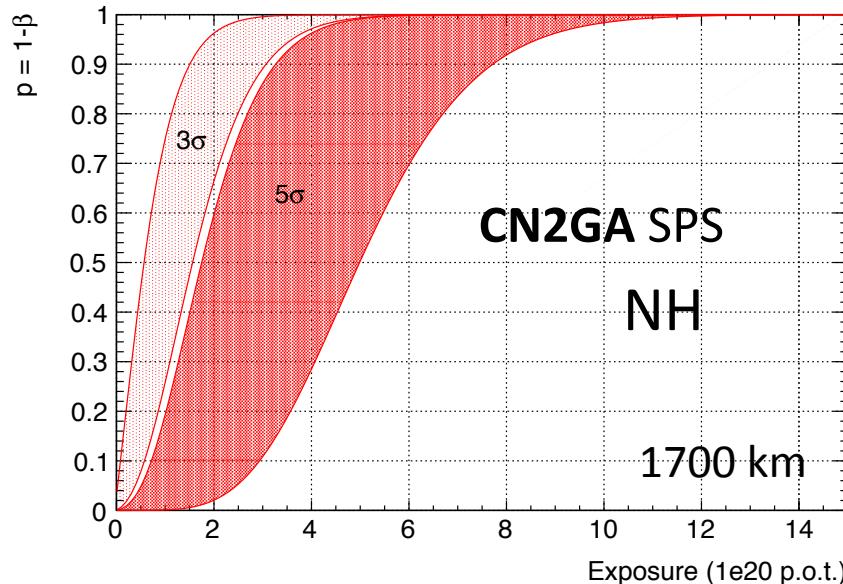
## LBNO@GARPENBERG

Power (NH) VS Exposure assuming 3 or 5 sigma Confidence Level  
20 kt SPS 400 GeV beam 1700 km

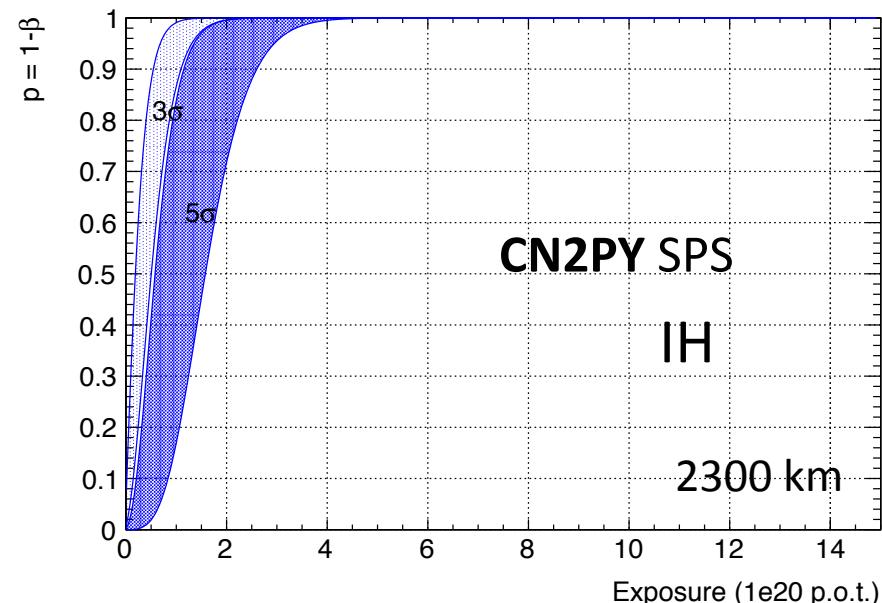
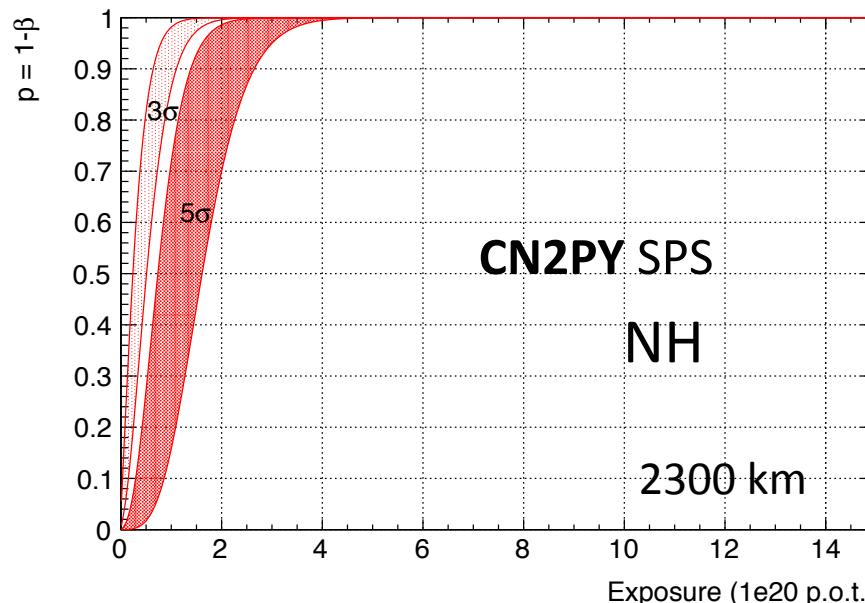


# MASS HIERARCHY SENSITIVITY

400 GeV SPS beam – 20 kt Liquid Argon Detector **LBNO@GARPENBERG**

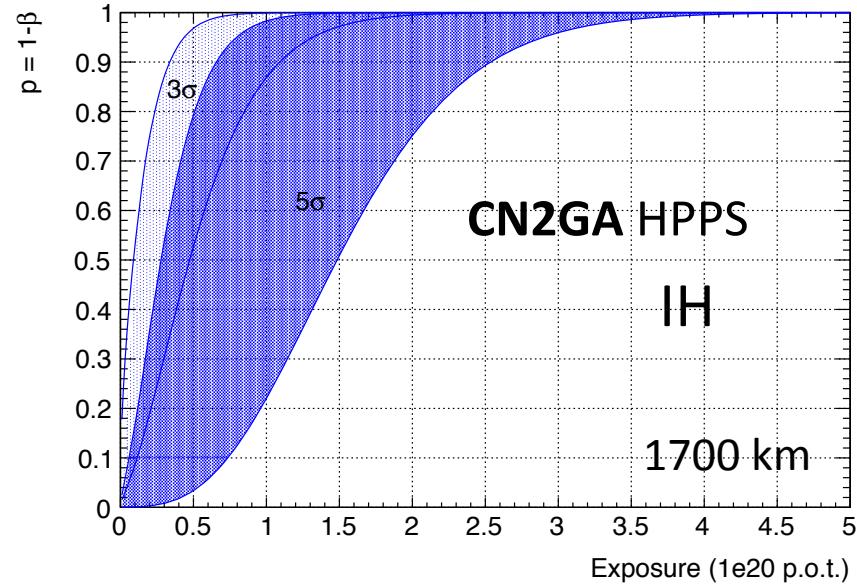
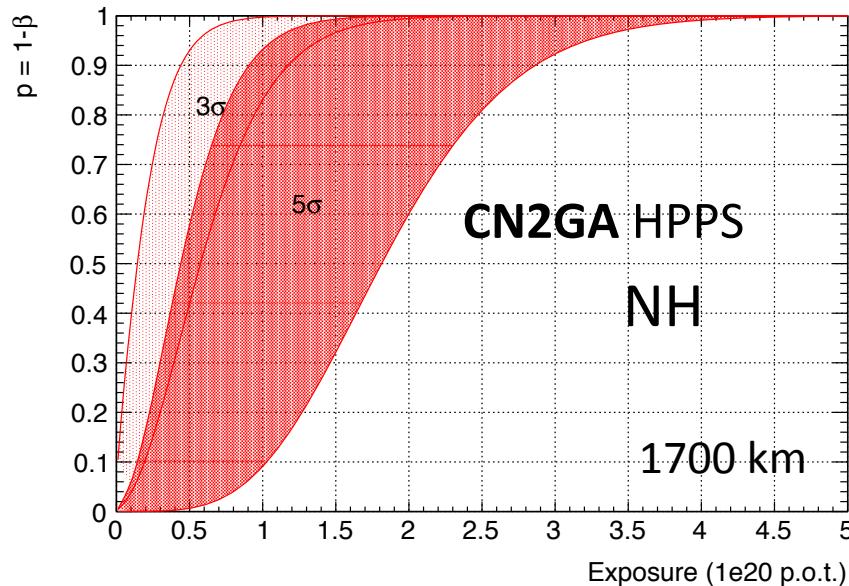


400 GeV SPS beam – 20 kt Liquid Argon Detector **LBNO: CERN TO PYHASALMI**

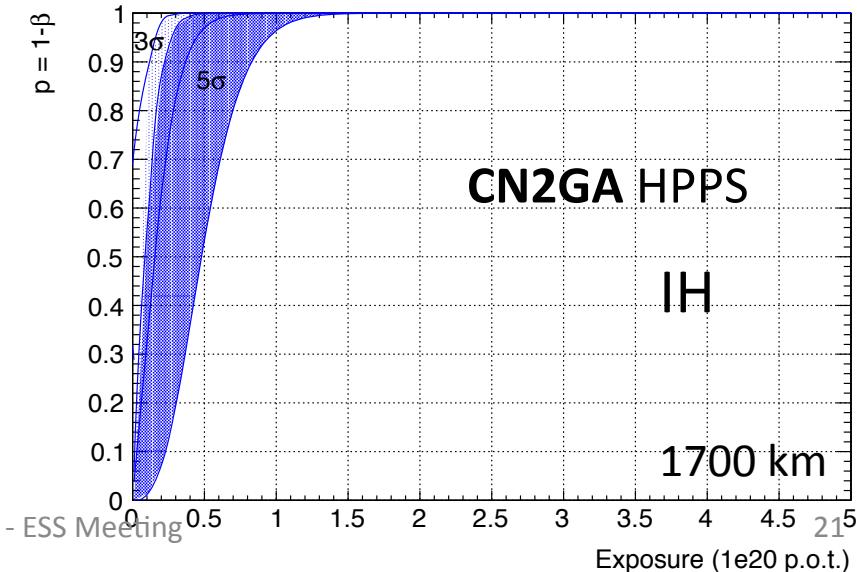
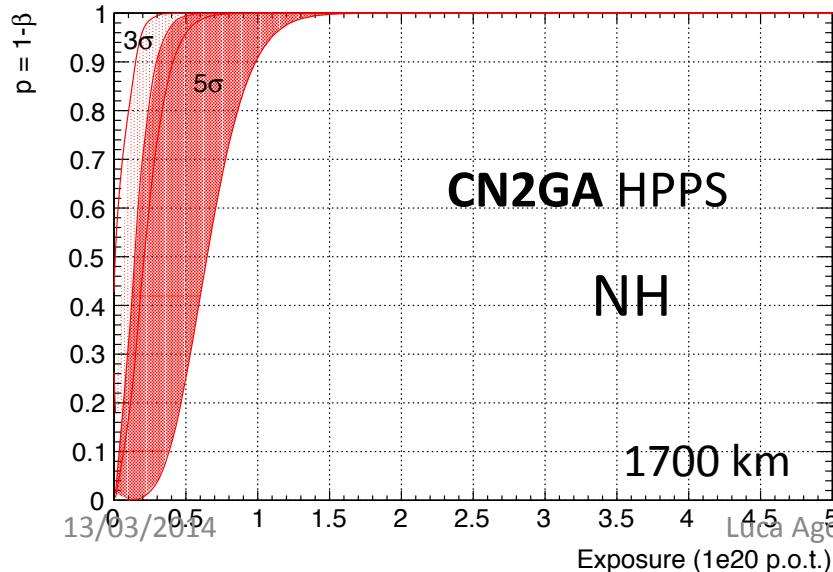


# MASS HIERARCHY SENSITIVITY : CN2GR HPPS

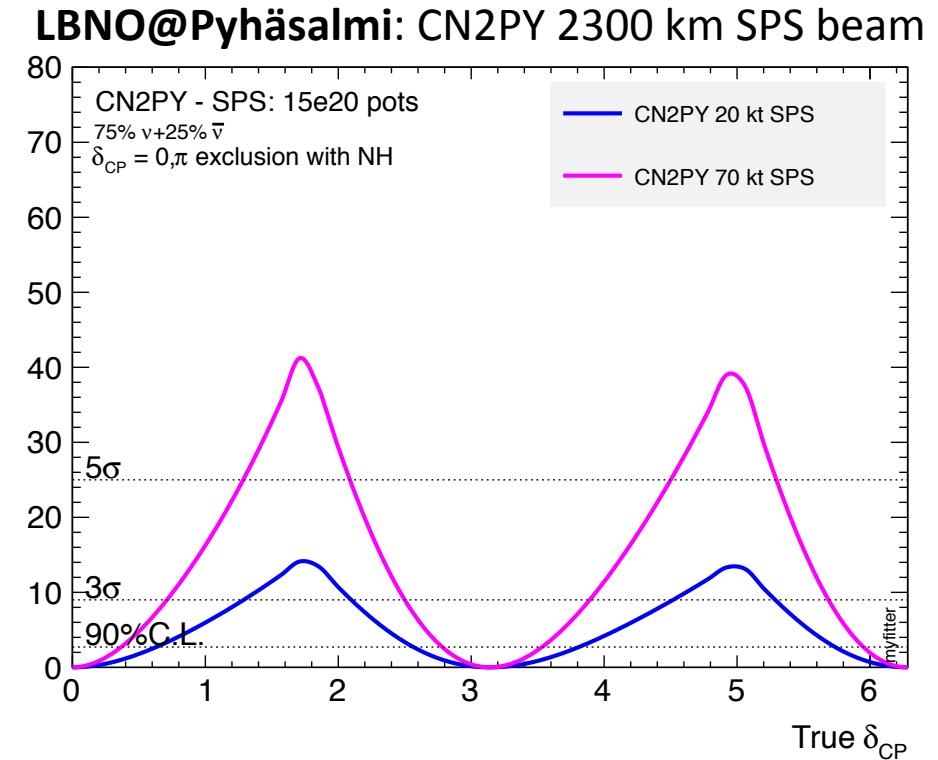
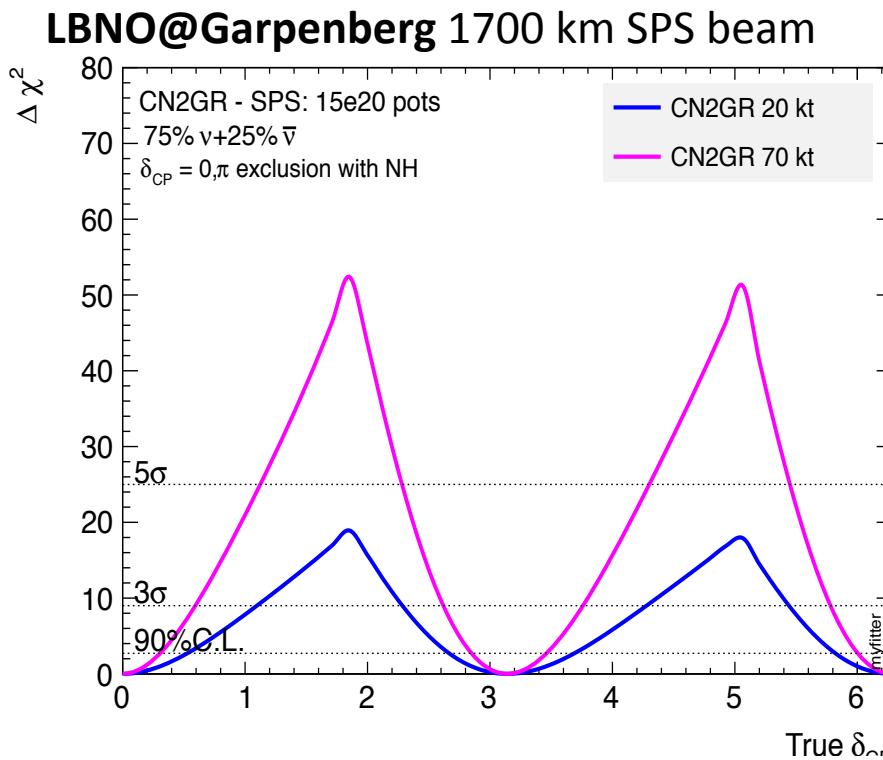
50 GeV HPPS beam – 20 kt Liquid Argon Detector **LBNO@GARPENBERG**



50 GeV HPPS beam – 70 kt Liquid Argon Detector **CN2GR**



# SENSITIVITY TO A CP PHASE DIFFERENT FROM 0 OR $\pi$ with 400 GeV SPS BEAM

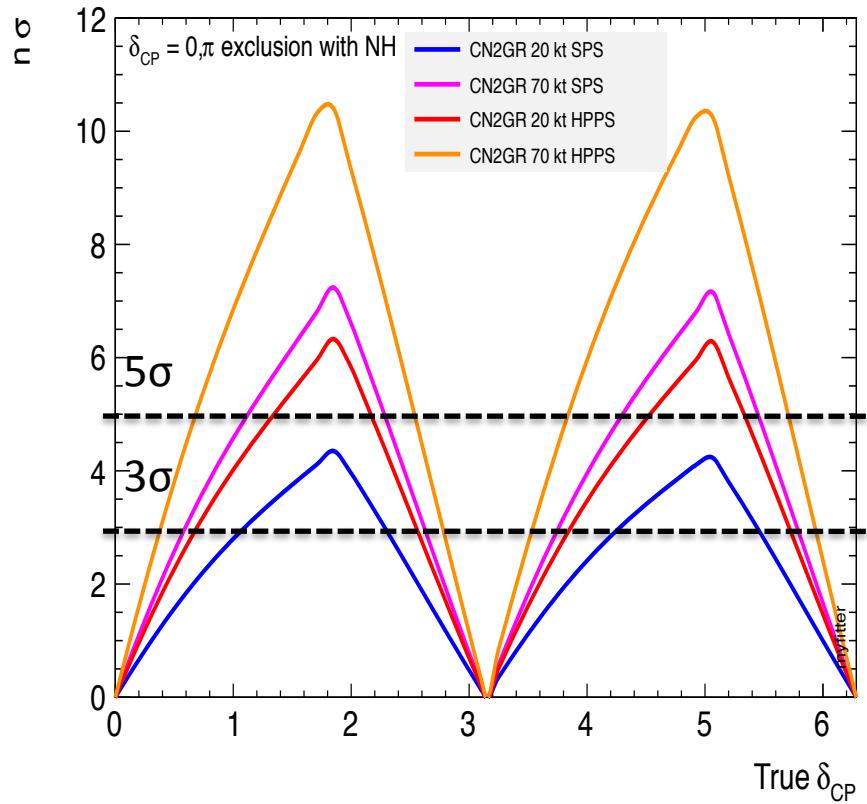


For both locations,  $\sim$ 10 years running:

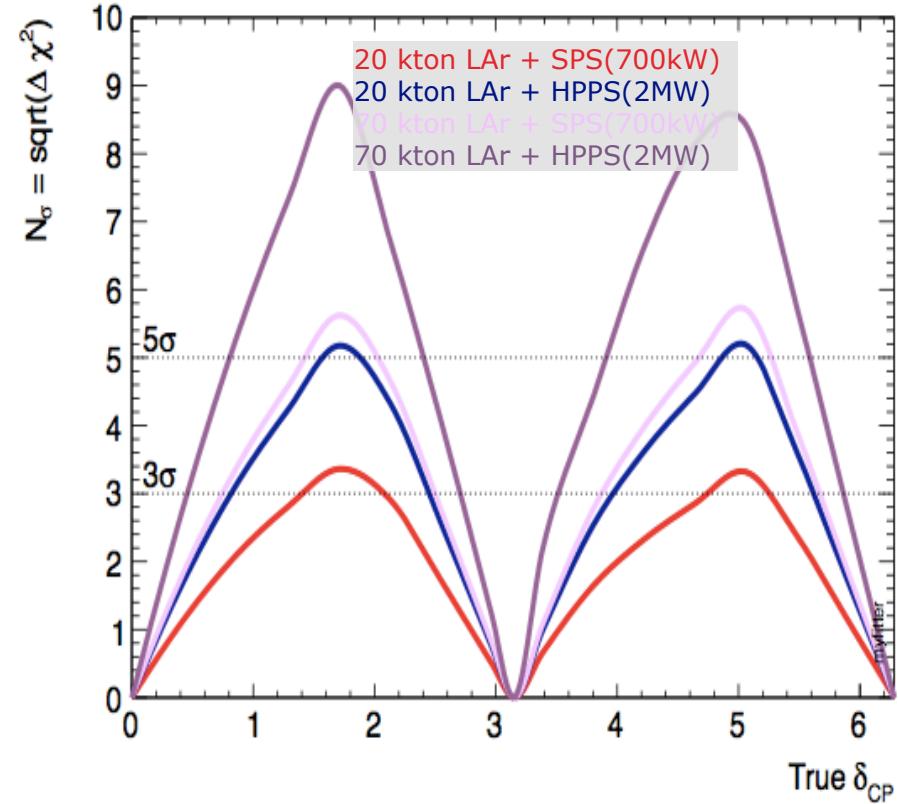
- 20 kt  $\rightarrow$  3 sigma 25%-30% of the phase space
- 70 kt  $\rightarrow$  3 sigma  $\sim$ 60%, 5 sigma 25%-35%

# $\delta_{CP}$ SENSITIVITY IN TERMS OF # of $\sigma$

**LBNO@Garpenberg**



**LBNO@Pyhäsalmi**



VERY SIMILAR PERFORMANCE AT THE TWO LOCATIONS  
To be noticed: the beam is not optimized for 1700 km

# CONCLUSIONS

- LBNO@PYHASALMI CAN MEASURE MH AT 5 SIGMA LEVEL AT A VERY EARLY STAGE (2 years)
- LBNO@GARPENBERG HAS COMPARABLE CP REACH BUT WE WOULD LOSE THE POSSIBILITY OF MEASURING MH AT THE EARLY STAGE
- HIGHER VALUES OF L/E COMPENSATE FLUX AND CROSS SECTION SUPPRESSIONS. SYSTEMATIC ERRORS BECOME LESS IMPORTANT
- BOTH CASES, LBNO@PY AND LBNO@GA, HAVE BETTER PHYSICS CASE THAN LBNO@HOMESTAKE
- 2300 km IS CLOSER TO THE MAGIC BASELINE ADEQUATE FOR MEASUREMENTS WITH A NEUTRINO FACTORY
- THE DEEP LOCATION ALLOWS A RICH ASTROPHYSICS PROGRAM AND THE NUCLEON DECAY MEASUREMENTS
- THE HIGH GRANULARITY OF THE LBNO LAr DETECTOR (GLACIER) PROVIDES VERY IMPORTANT SYNERGIES WITH A WC DETECTOR:
  - Different detector technologies
  - To Provide MH
  - To measure CP with the L/E behavior and the 1st and 2nd maximum

# **TACK TACK**

## **Acknowledgements:**

FP7 Research Infrastructure “Design Studies” LAGUNA-LBNO  
(Grant Agreement No. 284518, FP7-INFRA-2011-2.1.1.)

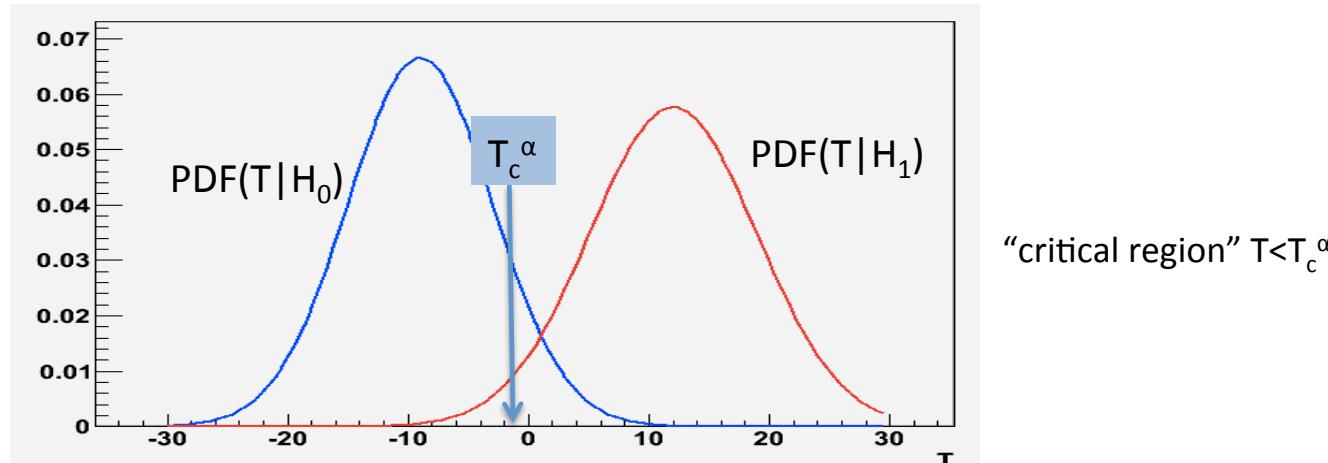
# BACKUP

# Test of hypothesis: the basics

Aim: test a “Null Hypothesis”  $H_0$   
against an “alternative hypothesis”  $H_1$ .

Method (“frequentist”):

- 1) define a “test statistic”  $T$ , function of the data
- 2) construct the PDF of  $T$  under each hypothesis
- 3) define a “critical region”  $\Omega_c$  such that  $T$  in  $\Omega_c$  suggests  $H_0$  is true



- 4) Evaluate the probability to give the wrong answer

# Test of hypothesis: the basics

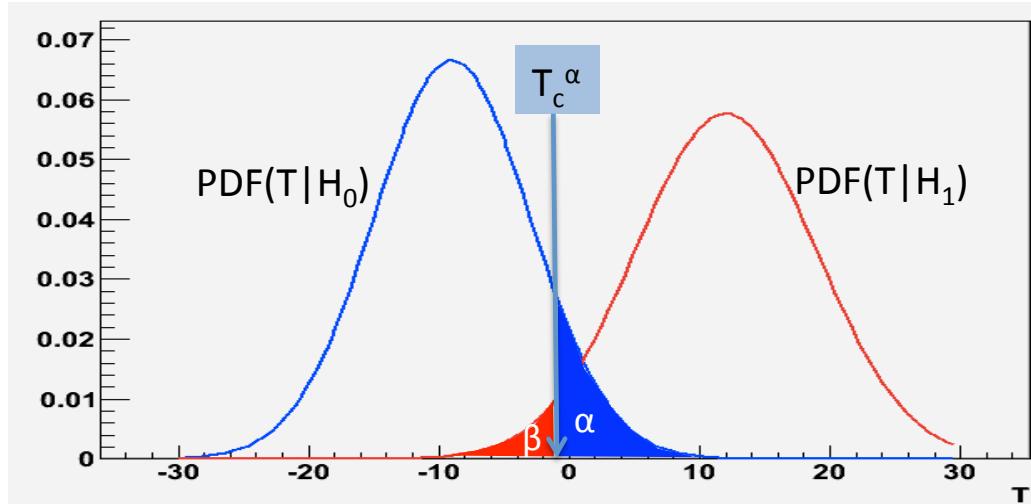
4) Evaluate the probability to give the wrong answer,

which you can do in two ways:

- reject  $H_0$  when it's true : Error of type I or "loss":  $\alpha$
- accept  $H_0$  when  $H_1$  is true: Error of type II or "contamination":  $\beta$

Definitions:  
Confidence Level  $CL = 1 - \alpha = \int_{-\infty}^{T_c} PDF(T | H_0) dT$

$$\text{Power } p = 1 - \beta = \int_{-\infty}^{T_c} PDF(T | H_1) dT$$



Note:  
"3 $\sigma$ " means  
 $\int_{-\infty}^{T_c} PDF(T | H_0) dT = 99.73\%$   
if 1-sided integrals are used

"critical region"  $T < T_c^\alpha$

reject  $H_0$  at  $CL (1 - \alpha)$   
if  $T > T_c^\alpha$